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DEPT OF AEROSPACE ENGINEERING G M FAETH ET AL

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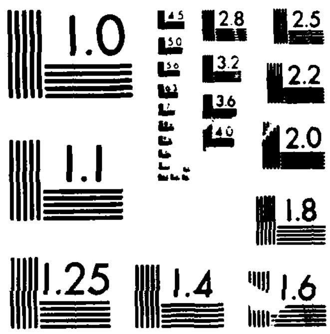

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G. M. Faeth and R. N. Parthasarathy

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1. Introduction

Turbulent multiphase flows, e.g., particle-laden jets, particle-laden flows in ducts, and sprays, have many applications which are important to the Air Force. This includes the combustion processes of airbreathing propulsion systems, solid fuel rocket engines for missiles, and solid and liquid propellant rocket engines for space applications. Research related to this problem is ongoing in this laboratory under Grant No. AFOSR-85-0244 entitled, "Dense-Spray Structure and Phenomena." This report describes activities under the DoD-University Research Instrumentation Program, Grant No. AFOSR-86-0248, which was designed to provide for the acquisition and development of unique instrumentation in support of this research.

All practical multiphase flows are turbulent. A central unresolved issue concerning these flows is turbulence/disersed-phase (particles, drops, etc.) interactions, e.g., the turbulent dispersion of the dispersed phase, the influence of turbulence on interphase transport properties (drag, heat transfer, and mass transfer), and the modification of continuous-phase turbulence properties by the dispersed phase (the last is often called "turbulence modulation"). These issues are being considered by experiments with large-scale liquid sprays in still air, and particle-laden flows in water (the last involves phase-density ratios which are representative of high-pressure combustion processes, but for test conditions where measurements are much easier to define and interpret). In both series of experiments, only interphase transport of momentum must be considered.

Quantities of primary interest for the experiments include the following: mean and fluctuating phase velocities; turbulence quantities for the dispersed phase, such as Reynolds stress, two-point and two-time velocity correlations, characteristic length and time scales, and power spectra, among others; number fluxes of the dispersed phase; and size and velocity correlations of the dispersed phase. The nature of the flows is such that these quantities must be measured nonintrusively in the presence of high concentrations of the dispersed phase. The objective of the work reported here was to complete an upgrade of an existing single-channel laser-Doppler anemometer (LDA), in order to provide an arrangement which can carry out these measurements.

All activities under the grant are discussed in this final report. Equipment purchases and instrument concepts are described in the next section. This is followed by a brief description of applications of the instrumentation completed thus far, as well as consideration of future near-term applications which are planned. The report concludes with a summary of articles and papers, project participants and oral presentations related to the present instrumentation development activities.

2. Instrumentation

2.1 Equipment purchases.

The present measurement requirements cannot be met with a single instrument configuration, thus flexibility was emphasized during development of the system. Specific design features of the LDA vary from one experiment to the next; however, two general configurations can be identified: (1) phase-discriminating LDA, which primarily provides capabilities of resolving the turbulence properties of the continuous phase, while avoiding biases due to the presence of the dispersed phase; and (2) phase-Doppler, which primarily provides the properties of the dispersed phase. Although each configuration tends to emphasize the properties of a particular phase, both have some capabilities to measure the properties of the other phase. The LDA upgrade was designed to provide both systems: they will be discussed in sections 2.2 and 2.3

The existing LDA was based on an argon-ion laser, using LDA components manufactured by TSI Inc., signal conditioning and acquisition equipment manufactured by LeCroy Research Systems Corp., and data storage and processing using an IBM 9002 microcomputer. Experience with these systems indicated very satisfactory performance for the single-channel LDA; therefore, consideration of system integration and compatibility mandated use of the same vendors for the LDA upgrade.

Equipment purchases are summarized in Table 1. These components are designed for use with an argon-ion laser, using the 488 and 514.5 nm lines of the laser, while adapting to existing TSI Inc. LDA components. The LeCroy Research Systems, Inc., equipment allows fast-trapping of LDA signals, which is needed to verify the performance of the LDA and to carry out phase-Doppler measurements, while also providing capabilities for Fourier analysis of signals in order to find power spectra and scales.

All the equipment listed in Table 1 was received and tested to show that performance specifications were met. Use of the equipment for phase-discrimination and phase-Doppler is described in the next two subsections.

2.2 Phase discrimination.

Phase discrimination is best applied to particle-laden flows. The configurations of interest involve relatively large (10-4000 μm) and nearly monodisperse particles in a continuous phase which is seeded with small particles (less than 1 μm) when measurements of continuous-phase velocities are made. Properties of interest include: single-point measurements of the velocities of the dispersed phase; particle number fluxes; single-point two-component measurements of the velocities of the continuous phase; and two-point single-component measurements of the velocities of the continuous

Table 1 Equipment Purchases

Quantity	Model No.	Description
Vendor: TSI, Inc., St. Paul, MN		
2	9178-1U	Rotating mount for beam splitter
2	9115-1U	Beam splitter
1	9180-11U	Frequency shifter (488 nm)
1	9180-12U	Frequency shifter (514.5 nm)
2	9113-9U	Beam spacer (9 mm)
4	9118U	Focusing lens (250 mm F.L.)
2	9179U	Rotating mount
2	9176U	Ring mount (4.25 in. height)
2	9140U	Receiving optics assembly
2	1988U	D/A converter (12 bit)
2	9121	Receiving optics base (10 in.)
1	9159	Color filter (488 nm)
1	9158	Color filter (514.5 nm)
2	9160	Photomultiplier system
2	1980B	Burst counter system
1	9149	Laser mount
1	TLS-1	Single color transmitting fiber optic link
Vendor: LeCroy Research Systems Corp., Spring Valley, NY		
1	9400	Digital oscilloscope
1	9400-WP01	Wave-form processor
1	9400-PW02	FFT package
Vendor: Newport Corp., Fountain Valley, CA		
3	SA-12	Solid aluminum breadboard (24 in. × 12 in.)
1	U1305P	He-Ne laser (5 mW)
Vendor: Oriel Corp., Stratford, CT		
1	11180	Low-profile optical bench
1	12320	Precision bench rod (70 mm)

phase.

These requirements can be met with either amplitude discrimination or phase-Doppler techniques: however, there are problems with both these approaches. Amplitude discrimination is based on the fact that large particles scatter more light than the small seeding particles used for LDA measurements of continuous-phase velocities. Thus, in principle, one can assign large amplitude signals (and the velocities measured from them) to the particles, and small-amplitude signals (and the velocities measured from them) to the seeding particles which are tracking the motion of the continuous phase. This presents no difficulty for finding particle properties, as long as the particles are significantly larger (an order of magnitude) than the LDA seeding particles – which is the case for flows of interest in this laboratory.

Use of amplitude discrimination alone, however, is not satisfactory for finding the velocities of the continuous phase, unless particle concentrations are very dilute – a situation which is not of much interest when turbulence/particle interactions are sought. The difficulty is that grazing collisions of large particles with the measuring volume generate small amplitude signals which can be incorrectly interpreted as coming from the seeding particles which represent the motion of the continuous phase. Thus, simple amplitude discrimination is inappropriate for present experimental objectives.

The phase-Doppler technique of Bachalo (1980) and Bachalo and Houser (1984) could be used to detect the size of the particle which was generating the signal, since this approach is designed to find particle size/velocity distributions. Unfortunately, this approach is not very effective when there is a large range of particle sizes to be considered, e.g., that approach cannot treat seeding particles of ca. 1 μm and flow particles of ca. 1 mm, which is typical of experiments of particle-laden flows.

The phase-discriminating LDA avoids these difficulties, and is the method of choice for detailed measurements of continuous-phase velocities in particle-laden flows. The approach was first used by Modarress et al. (1984). For a simple single-channel LDA, the technique involves use of a third beam having a different color than the two intersecting LDA beams. The third beam is focussed and observed so that its measuring volume surrounds the LDA measuring volume. The measuring volume of the third beam is sized so that the largest particle yields a good signal even when the particle just grazes the LDA measuring volume. The procedure is to scan the intensity record from the third beam and discard all LDA measurements from the record of the continuous phase, when a strong third beam signal indicates the presence of a large particle in the vicinity of the LDA measuring volume.

The system developed under the present grant can be either a single-point two-component phase-discriminating LDA, involving five laser beams; or a two-point single-component LDA, involving six laser beams. The five beam system involves two orthogonal real fringe patterns, constructed from pairs of intersecting beams of the 488 and 514.5 nm lines of an argon-ion laser, with the 632.8 nm line of an HeNe laser used as the fifth, phase-discriminating, beam. The six beam system also has real fringe patterns based on the 488 and 514.5 nm lines of an argon-ion laser; however, in this case, one LDA measuring volume can be traversed independently of the other (in two directions); therefore, each LDA measuring volume has a third 632.8 HeNe phase discriminating system. A flexible traversable LDA probe volume was achieved by transmitting the laser beam to the sending optics of this system through an optical fiber. In addition to two velocity signals, the arrangement also provides particle number fluxes by counting particle crossings of the measuring volume, using a pulse counter. Thus far, this system has been used in single-channel one-point, and two-channel two-point configurations. Additional details concerning these arrangements will be discussed in Section 3.

2.3 Phase Doppler.

Phase Doppler is best applied to polydisperse flows, like sprays. This concept was developed by Bachalo (1980) and Bachalo and Houser (1984). This concept is based on the fact that a particle which scatters light from a dual-beam LDA probe volume creates a real fringe pattern in the space around it which is related to the diameter of the particle. In fact, when the particle is moving it is the motion of this fringe pattern across a photodetector that yields the Doppler signal that is used for measuring velocities.

While the temporal frequency of the Doppler signal is independent of particle size, the spatial variation of the scattered fringe pattern can be used to find the particle diameter if the optical properties of the particle and continuous phases are known. The spatial pattern is complex, but can be computed based on Mie scattering theory for a general solution. Fortunately, the strongest signals can be analyzed more simply with diffraction giving the fringe pattern in the forward scattering direction, refraction with no internal reflections giving the fringe pattern near 90°, and first reflection giving the fringe pattern in the backward scattering direction (Bachalo 1980). Such analysis yields relationships between the wavelength of the spatial fringe pattern and the size of the particle which can be found rapidly – even with a microcomputer.

The present system can be configured to yield single-point single-component velocity and size correlations, using an arrangement similar to Bachalo (1980) and Bachalo and Houser (1984). This is based on a simple dual-beam LDA arrangement using the 514.5 nm line of an argon-ion laser. The system is to be used for measurements in dense sprays, where optical access is limited; therefore, only refraction and reflections are used in order to limit optical path lengths in the spray. The scattered light signal is measured by three detectors positioned circumferentially to the measuring volume in a plane normal to the optical plane. The signals are trapped using LeCroy, high frequency (100 MHz) a/d converters. Phase differences between the detector outputs are determined by zero crossing analysis. The phase difference between any two detectors is sufficient to yield the particle diameter. Two determinations of this type allows accuracy to be checked, and the dynamic range of the measurement increased, while eliminating effects of size aliasing.

The problem with the present approach is that signal processing is relatively slow, limiting data rates to a few samples per second. Commercial phase-Doppler systems can be purchased which have far greater data rates and are much more convenient to use for routine measurements than the present system. However, these systems are not designed for use in reflection and for high speed flows of interest in studies here; therefore, the present arrangement provides unique capabilities to treat difficult measuring conditions, in a research environment, where high data rates are not a major factor.

3. Applications

3.1 Particle-laden jets.

The phase-discriminating LDA and particle number flux systems were the main focus of instrumentation development during the present investigation. A single-channel system was developed and used for measurements in particle-laden jets, which will be discussed in this subsection; and a two-channel two-point system was developed for measurements of turbulence modulation, which will be discussed in Section 3.2. Future applications of the instrumentation, emphasizing the phase-Doppler configuration, will be discussed in Section 3.3

The single-channel phase-discriminating LDA, used for measurements in the particle-laden jets, is illustrated in Fig. 1. The LDA was a conventional dual beam system, operating with the 514.5 line of an argon-ion laser. Forward-scattering detection, as shown in Fig. 1, was used for measurements of continuous-phase velocities. Off-axis detection was used for particle velocities, to avoid the strong pedestal signals of particles and to improve signal-to-noise ratios (Sun & Faeth, 1986). A Bragg cell frequency shifter was used to eliminate directional bias and ambiguity. Signal levels from the naturally-seeded water were much smaller than for the particles; therefore, simple amplitude discrimination served to identify particle velocity signals. This involved reducing the gain of the detector circuit until only signals from particles were recorded, i.e., ending the flow of particles invariably resulted in no further signals being processed. A burst-counter signal processor (TSI, Model 1990C) was used to find particle velocities. The output of the burst counter was stored on a microcomputer (IBM 9002) and subsequently processed to yield particle-averaged mean and fluctuating

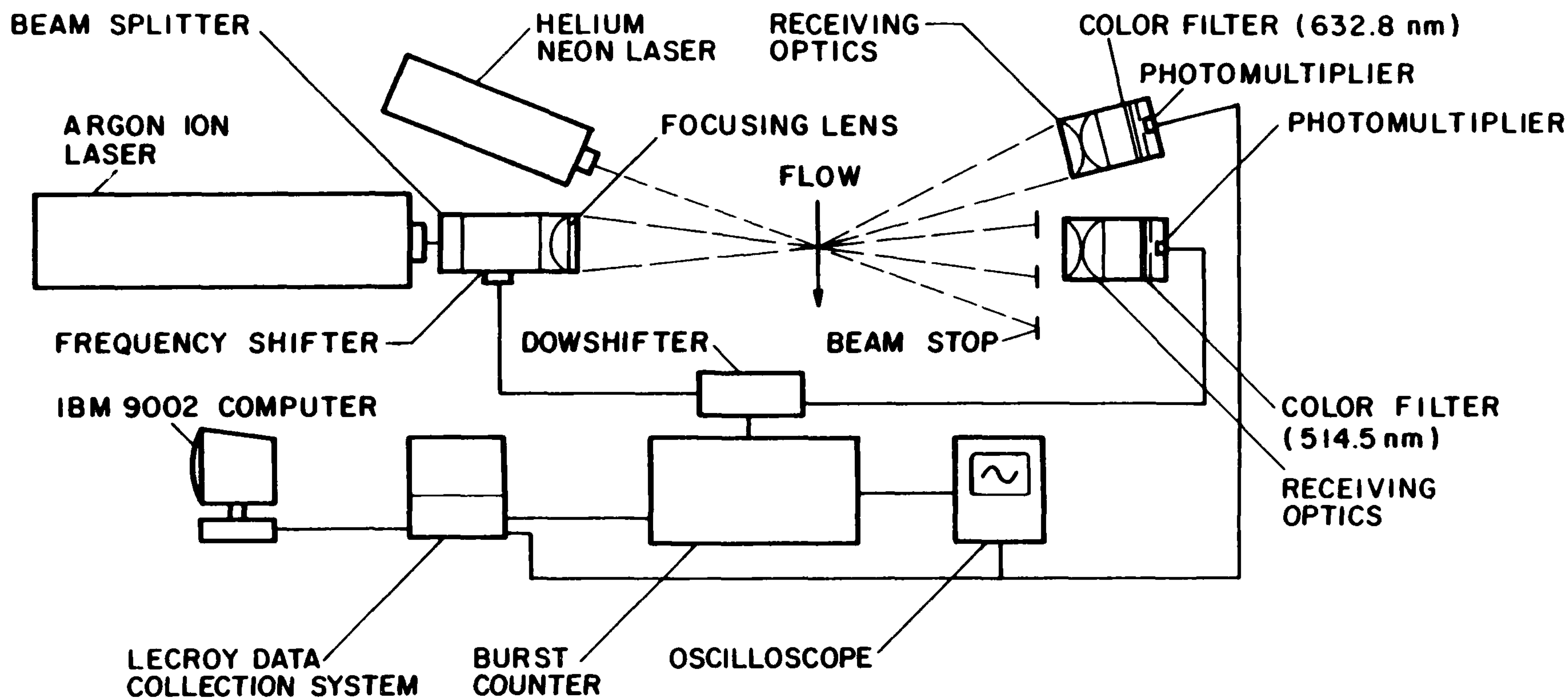

Figure 1. Sketch of single-channel phase-discriminating laser-Doppler anemometer.

velocities. Streamwise and radial velocities were measured by appropriately orienting the plane of the LDA beams.

Phase discrimination was used to obtain continuous-phase velocity signals, as discussed earlier. The arrangement is illustrated in Fig. 1. A HeNe laser, operating at 632.8 nm, was used for phase discrimination, with a detector observing light scattered from this beam through a laser-line filter. The beam waist, the collecting optics, the direction of the laser beam, and the direction of the collecting optics, were selected so that all grazing collisions of the particles with the LDA measuring volume were detected (the region viewed by the phase discriminator had a diameter greater than the sum of the largest particle and measuring volume diameters). The data processing system recorded the discriminator signal and eliminated all LDA records where a pulse on this beam indicated a particle near the measuring volume. The remaining output from the continuous phase was a high data-density signal from the d/a conversion of the sample-and-hold circuit at the output of the burst counter (the time between valid measurements was small in comparison to the integral time scale of the flow). This signal was time averaged (ignoring periods when particles were present) to obtain unbiased time-averaged mean and fluctuating continuous-phase velocities. Various velocity components and the Reynolds stress were obtained by rotating the LDA beam plane, similar to past work (Shuen et al., 1985; 1986; Solomon et al. 1985, 1985a; Sun & Faeth, 1986; Sun et al., 1986).

The Mie scattering system for particle number flux measurements was similar to Sun et al. (1986). A HeNe laser beam was passed through an aperture to yield a primary beam having a nearly uniform intensity, which was directed to the measuring volume. The beam was observed, in a normal direction, by a detector. The output of the detector was recorded with a pulse counter having an adjustable threshold. As particles passed through the measuring volume, they generated light pulses by Mie scattering. This signal was detected by the pulse counter, using the threshold to control spurious background signals. The crossectional area of observation was calibrated by collecting particles from a uniform flow.

Complete details concerning the experimental arrangement and the findings of the liquid jet study are reported by Parthasarathy & Faeth (1987, 1987a). Test conditions are summarized in Table 2. The test flows involved a water jet (as a baseline) and two particle-laden water jets, all in still water. Injection was vertically downward from a long constant area passage. Reynolds numbers were on the order of 9000; therefore, the flows were reasonably turbulent.

Some example measurements using the phase-discriminating LDA and Mie scattering systems are illustrated in Figs. 2-8. Figures 2-4 were obtained at x/d = 8, where x is distance from the injector, which has a diameter d. This position was used

Table 2. Summary of Particle-Laden Jet Test Conditions[+]

Flow	Single-Phase Jet	Particle-Laden Jet I	Particle-Laden Jet II
Mass loading ratio (%)[†]	0.0	5.9	11.8
Particle volume fraction (%)	0.0	2.4	4.8
Water flowrate (ml/s)	32.7	32.7	32.7
Initial average velocity (m/s)	1.61	1.66	1.72
Jet Reynolds number[f]	8530	8795	9115

[+]Initial conditions for a particle-laden water jet injected vertically downward in still water. Injector is a constant-area passage (diameter of 5.08 mm and length of 350 mm). Water temperature of 298 ± 2K.

[†]Mass of particles per unit mass of water. Particles are round glass beads having a number mean diameter (NMD) of 501 μm, a standard deviation from the NMD of 45 μm, a Sauter mean diameter (SMD) of 505 μm, and a density of 2450 kg/m^3.

[f]$Re = u_o d/\nu$, where d is the injector diameter and ν is the kinematic viscosity of water.

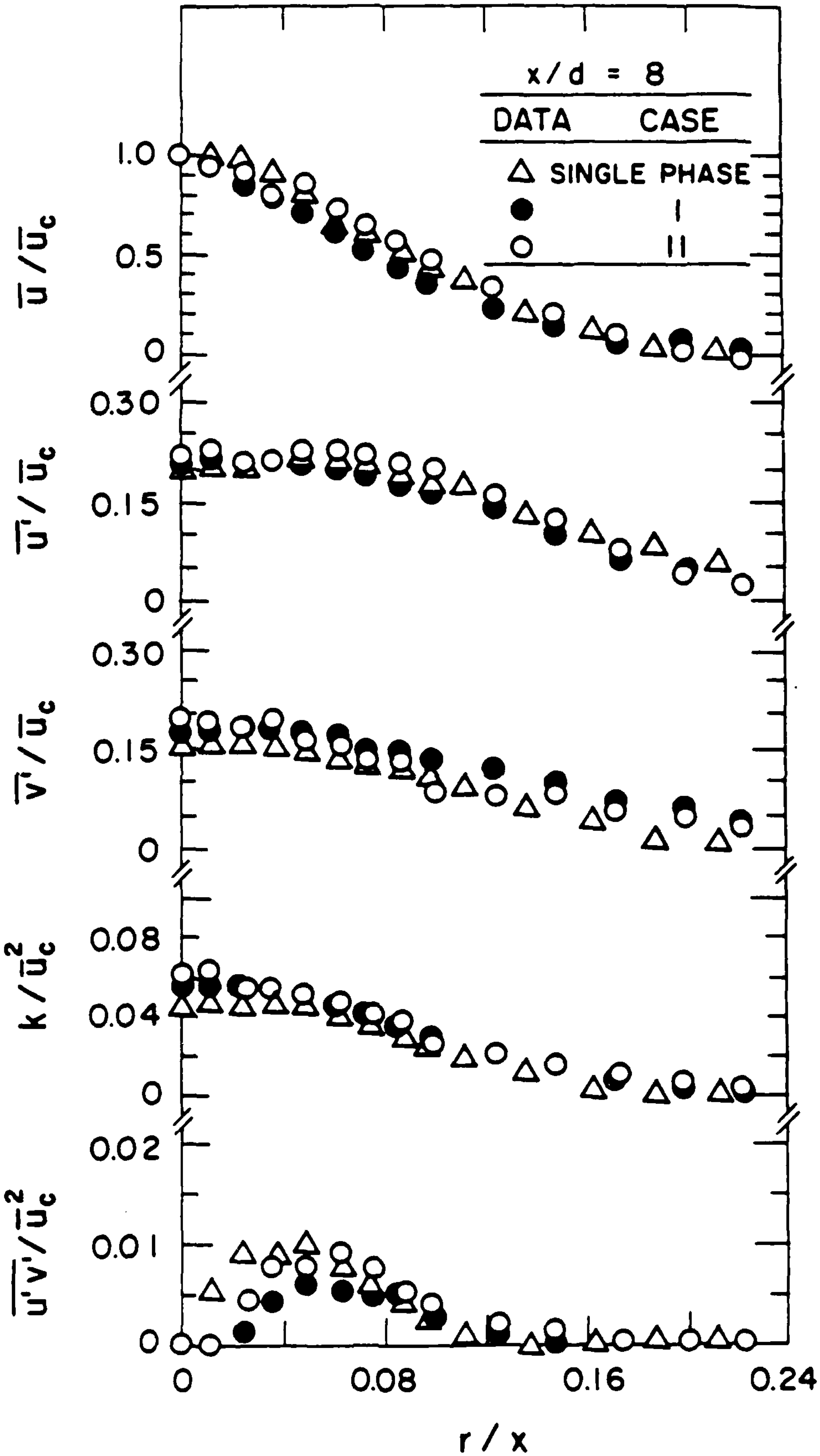

Figure 2. Liquid-phase velocities near the injector of pure and particle-laden liquid jets.

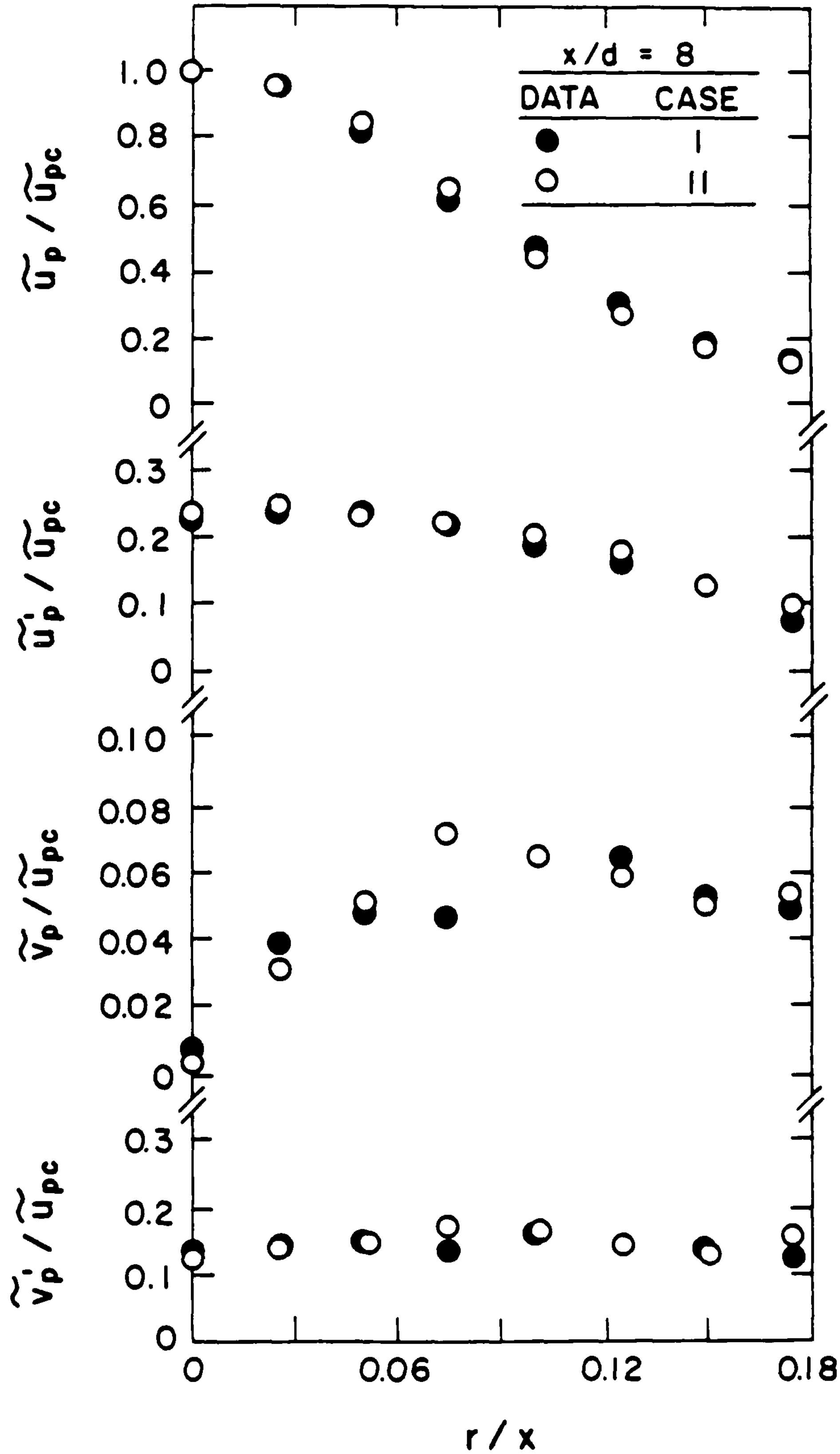

Figure 3. Particle velocities near the injector of particle-laden jets.

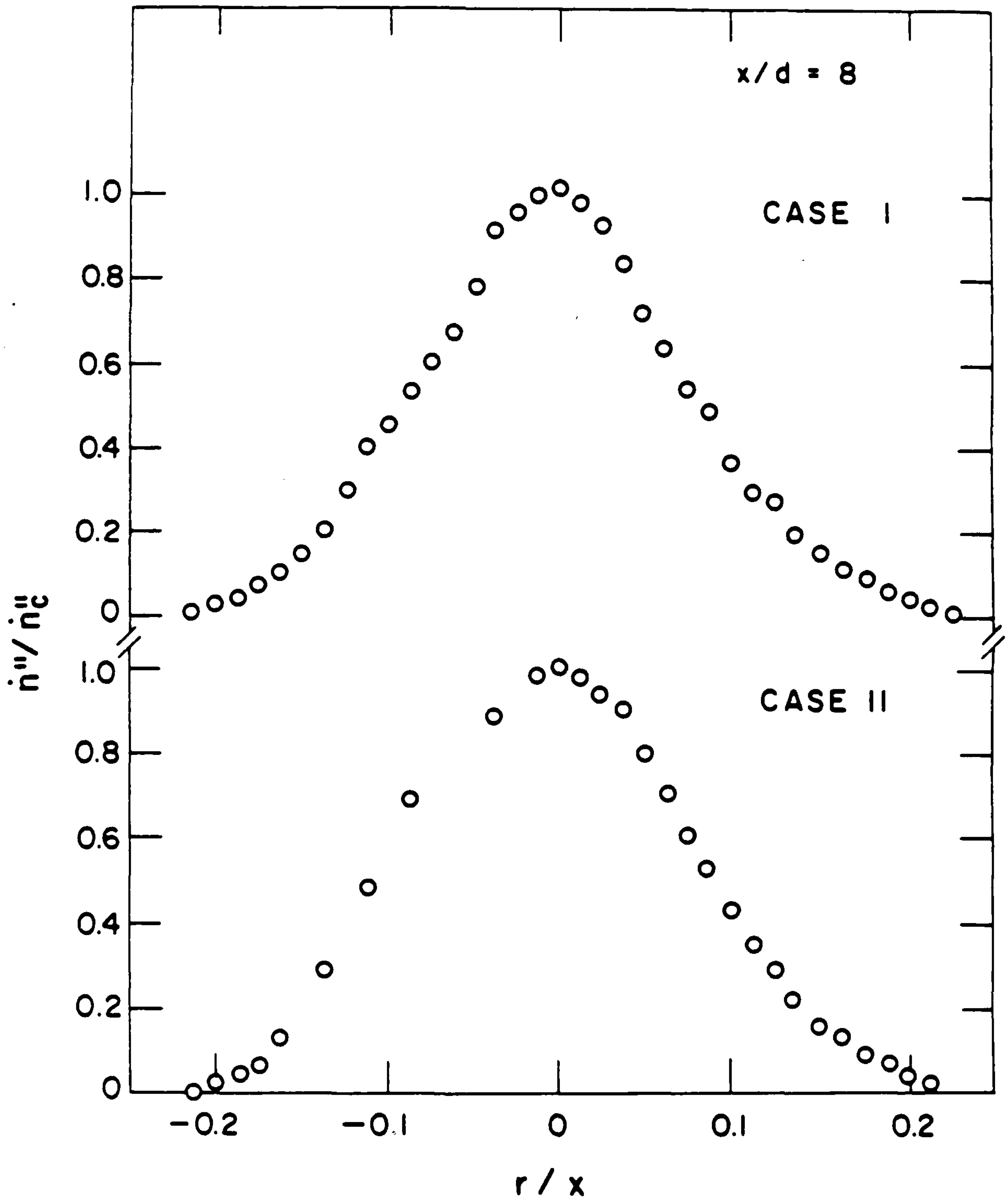

Figure 4. Particle number fluxes near the injector of particle-laden jets.

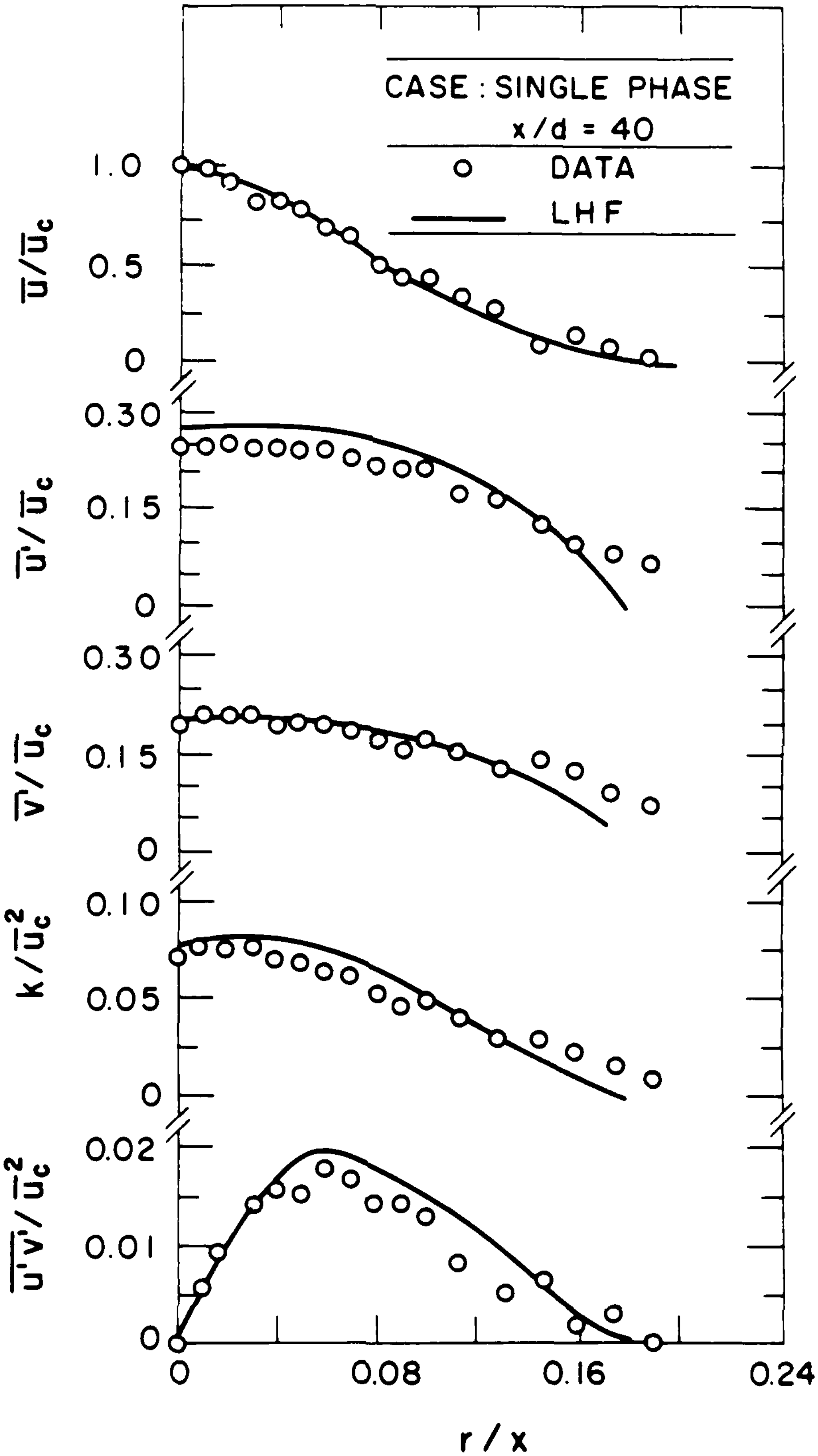

Figure 5. Liquid-phase properties in a liquid jet (x/d = 40).

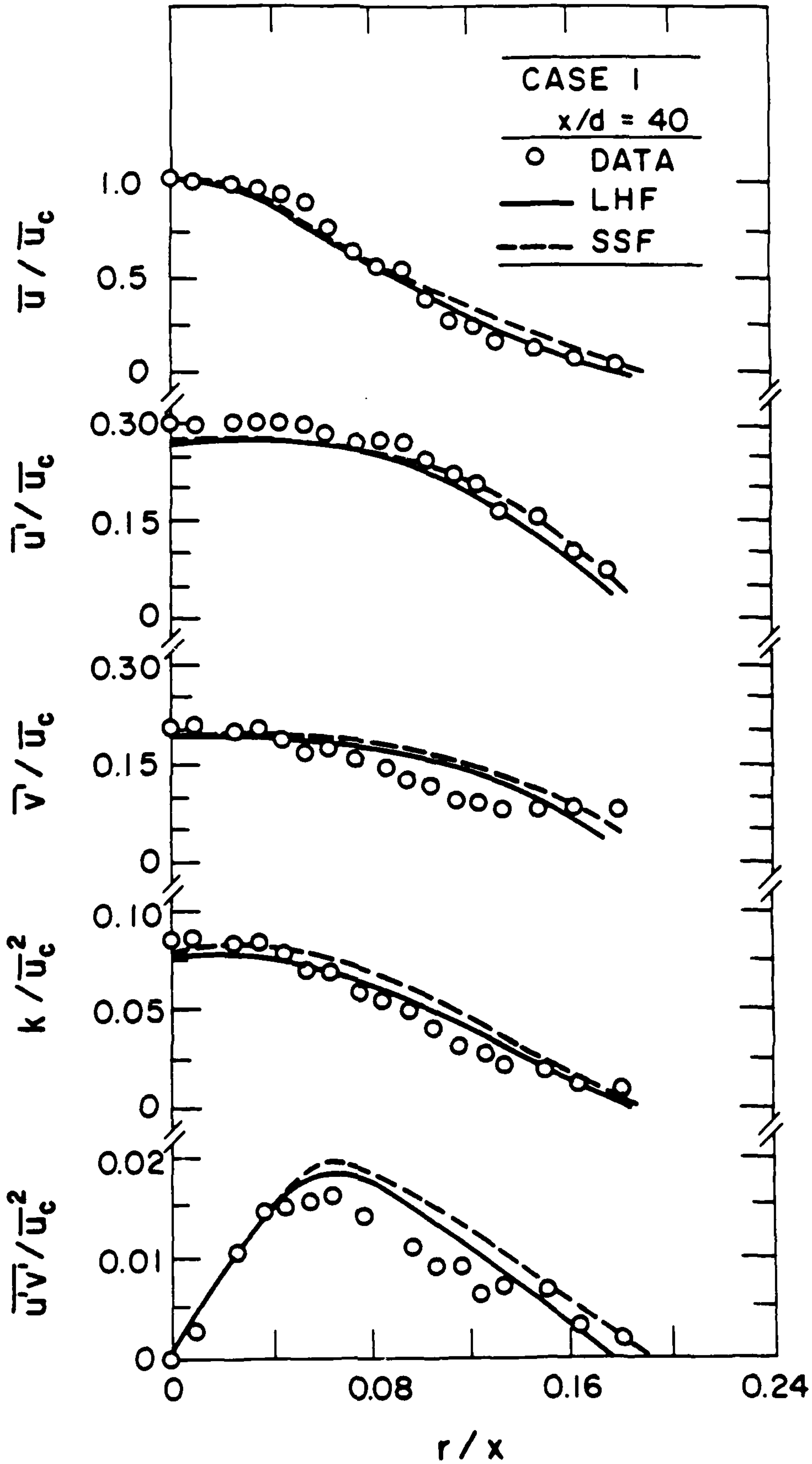

Figure 6. Liquid-phase properties in a particle-laden liquid jet. (Case I, x/d = 40).

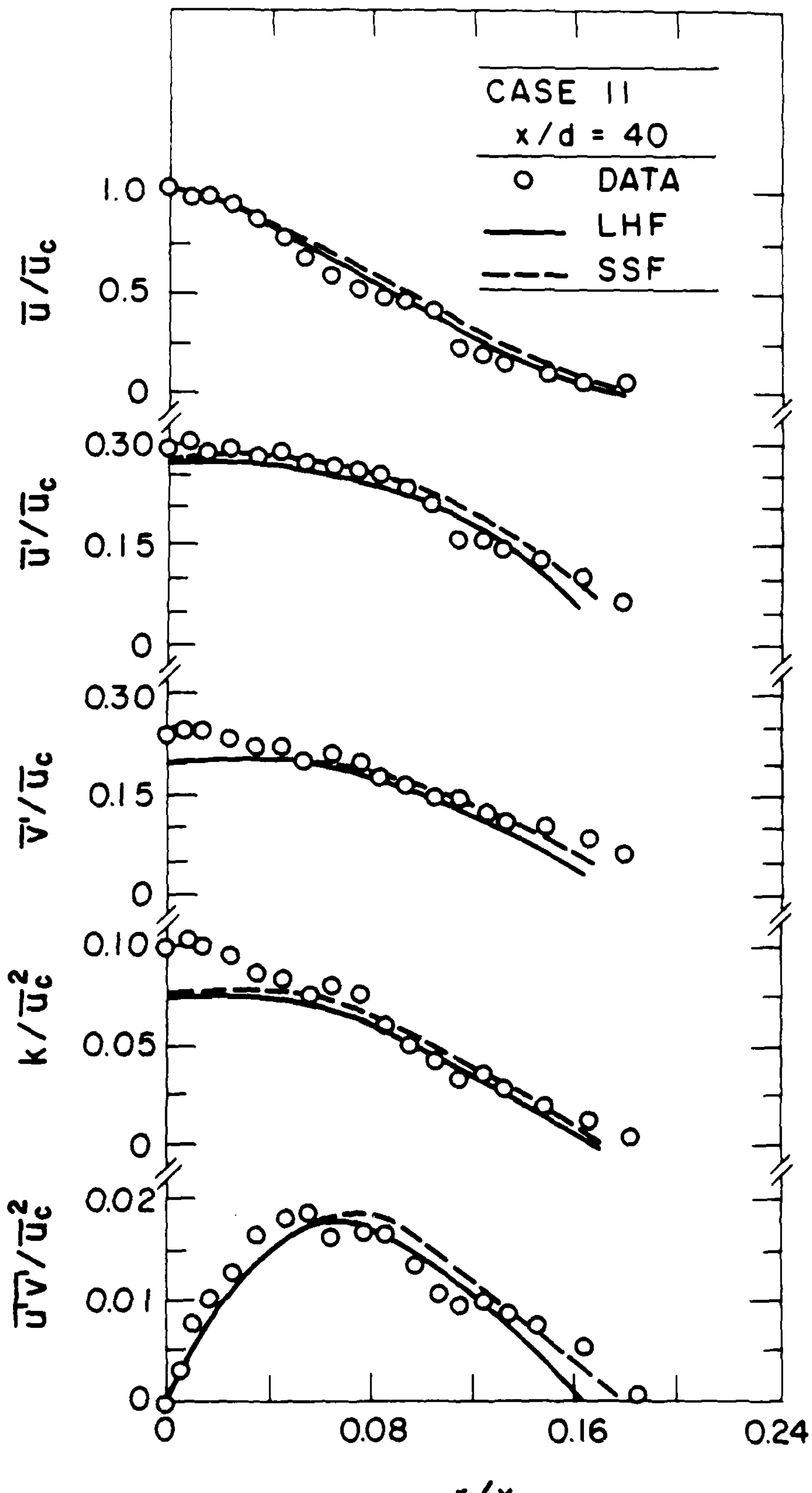

Figure 7. Liquid-phase properties in a particle-laden liquid jet. (Case II, x/d = 40).

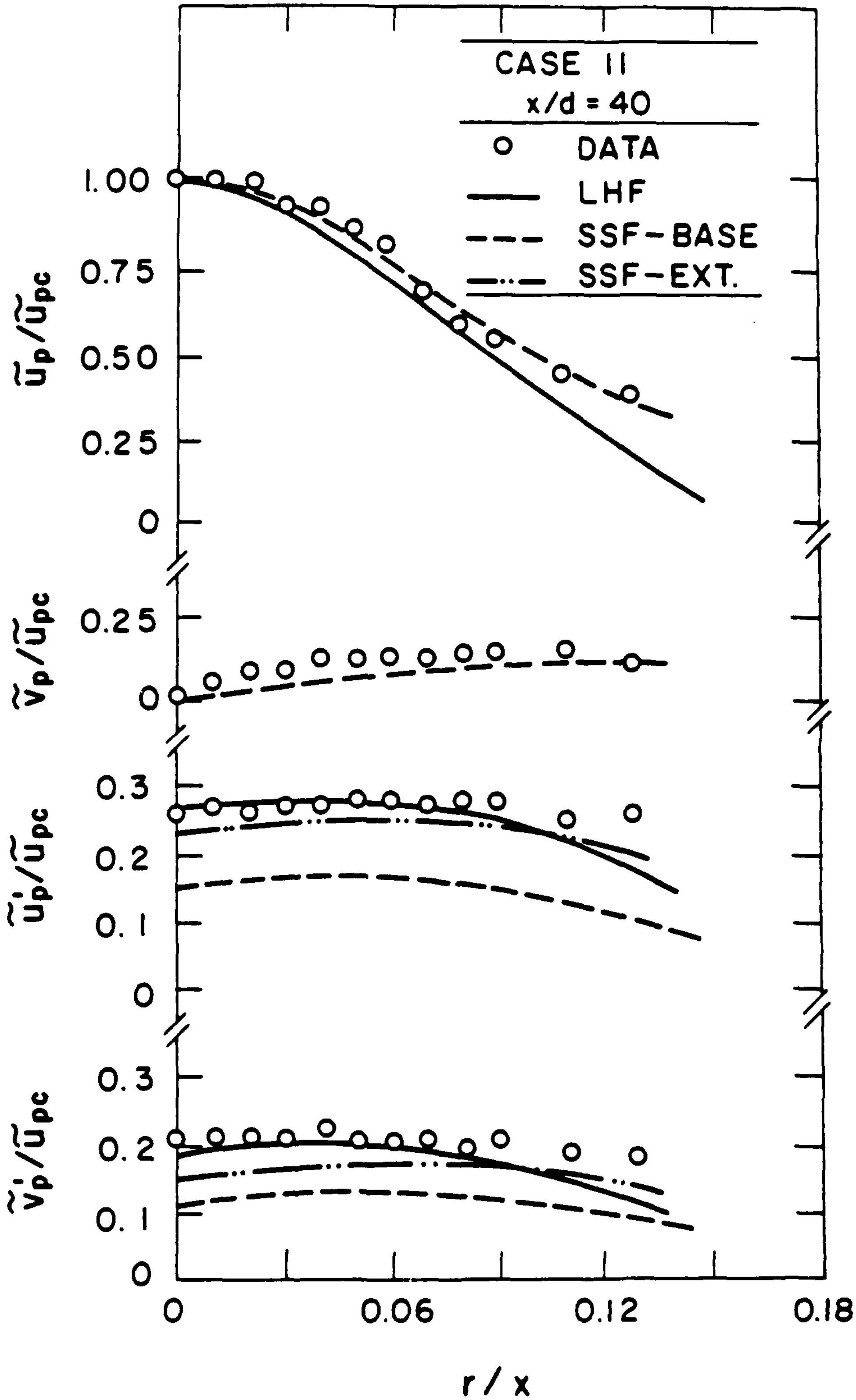

Figure 8. Particle properties in a particle-laden liquid jet. (Case II, x/d = 40).

as an initial condition for separated flow analysis of the flows, since the laser beams could not penetrate the particle-laden flows nearer to the injector. Liquid-phase properties are illustrated in Fig. 1. Time-averaged mean and root-mean-squared fluctuating streamwise, $\bar{u}$, $\bar{u}'$, and radial, $\bar{v}$, $\bar{v}'$ velocities, the turbulence kinetic energy, k, and the Reynolds stress, $\overline{u'v'}$, are plotted as a function of radial distance, r, normalized by x. The subscript c denotes centerline properties. These results have fundamental interest since they exhibit effects of turbulence modulation; in particular, the particle laden flows have higher velocity fluctuations and values of k, and lower Reynolds stresses near the axis. These changes are caused by the additional dissipation of the potential energy of the particles, which is most evident near the axis where conventional mechanisms of turbulence production by the continuous phase (shear production) are small.

Initial particle velocities are illustrated in Fig. 3, where $\tilde{u}_p$, $\tilde{u}'_p$ and $\tilde{v}_p$, $\tilde{v}'_p$ denote particle-averaged mean and root-mean-squared fluctuating streamwise and radial particle velocities. Particle velocity fluctuations are strongly anisotropic near the axis, but become more isotropic near the edge of the flow. $\tilde{v}_p$ is difficult to measure, since it is very small: notably, $\tilde{v}_p$ remains positive near the edge of the flow, since no particles are entrained from the surroundings.

Particle number fluxes, $\dot{n}''$, are plotted in Fig. 4 for x/d = 8. These distributions are reasonably symmetric about the axis, and satisfy total particle conservation requirements within 10 percent, which is well within experimental uncertainties; therefore, the flux measuring system and the experiment operated reasonably satisfactory.

Results pictured in Figs. 2-4 demonstrate satisfactory performance of the single-channel phase-discriminating LDA, serving the purposes of this report. However, some additional results of the particle-laden jet experiments will be considered in order to introduce effects of turbulence modulation to be considered next.

The capability of particles to modify turbulence properties, even for very dilute flows where accurate measurements of continuous flow properties can be made, is illustrated in Figs. 5-7. Continuous-phase properties are plotted at x/d = 40 for the single-phase jet and for the two particle-laden jets. Predictions shown on these plots allow for effects of particles on the mean motion, but these changes are small since the flows are dilute, i.e. all the predictions of liquid properties are essentially the same for the three flows when plotted in the manner of Figs. 5-7. Effects of turbulence modulation were ignored for the predictions, since rational methods of dealing with turbulence modulation phenomena are unknown at present. The interesting feature is that liquid-phase velocity fluctuations (and k) progressively increase near the axis, as the particle loading is increased: this is a direct effect of turbulence modulation. As noted earlier, the effect of turbulence modulation is most evident near the axis since production of turbulence by liquid shear forces is negligible in this region. This observation was exploited in planning specific studies of turbulence modulation, to be discussed in the next subsection.

Particle velocities for the most highly-loaded particle-laden jet, at x/d = 40, are illustrated in Fig. 8. An interesting effect found here is that particle drag coefficients are unusually high, due to the high relative turbulence intensities seen by particles (Parthasarathy & Faeth, 1987, 1987a). Effects of small-scale turbulence, produced directly by particles, on particle drag coefficients are also suspected. Treating these problems, however, requires information on turbulence spectra and length scales. The more advanced phase-discriminating LDA, to be discussed next, was designed to provide such measurements.

3.2 Turbulence modulation.

Turbulence modulation is being studied using an arrangement where the particles are the source of turbulence production. This involves a water-filled tank with a uniform flux of particles falling through the tank. In this case, the mean velocity of the continuous phase is nearly zero and the particles create a homogeneous turbulent field. Along with conventional measurements of phase velocities and particle fluxes, power spectra are needed to gain an understanding of turbulence/particle interactions. Furthermore, two-point measurements, considering the streamwise (mean particle direction) and crosstream directions, are needed to identify spatial scales. The last is of great importance, since the scales relevant to particle-generated turbulence, and their relationship to scales generated by continuous-phase shear in more conventional flows, are major issues. This information can only be generated by two-point velocity measurements for the continuous phase.

The arrangement of the two-channel/two-point phase-discriminating LDA is illustrated in Fig. 9. A photograph of the system, installed on the turbulence-modulation experiment, appears in Fig. 10. The photograph was taken from a point behind the sending optics of the traversable LDA channel. The system uses a single argon-ion laser, operating in the all-lines mode. The green (514.5 nm) and blue (488 nm) lines are separated with a dichroic green mirror. The green line is frequency shifted and then used for a stationary LDA whose measuring volume is at the center of the tank. A HeNe laser beam provides the phase-discriminating beam for this channel. The LDA and

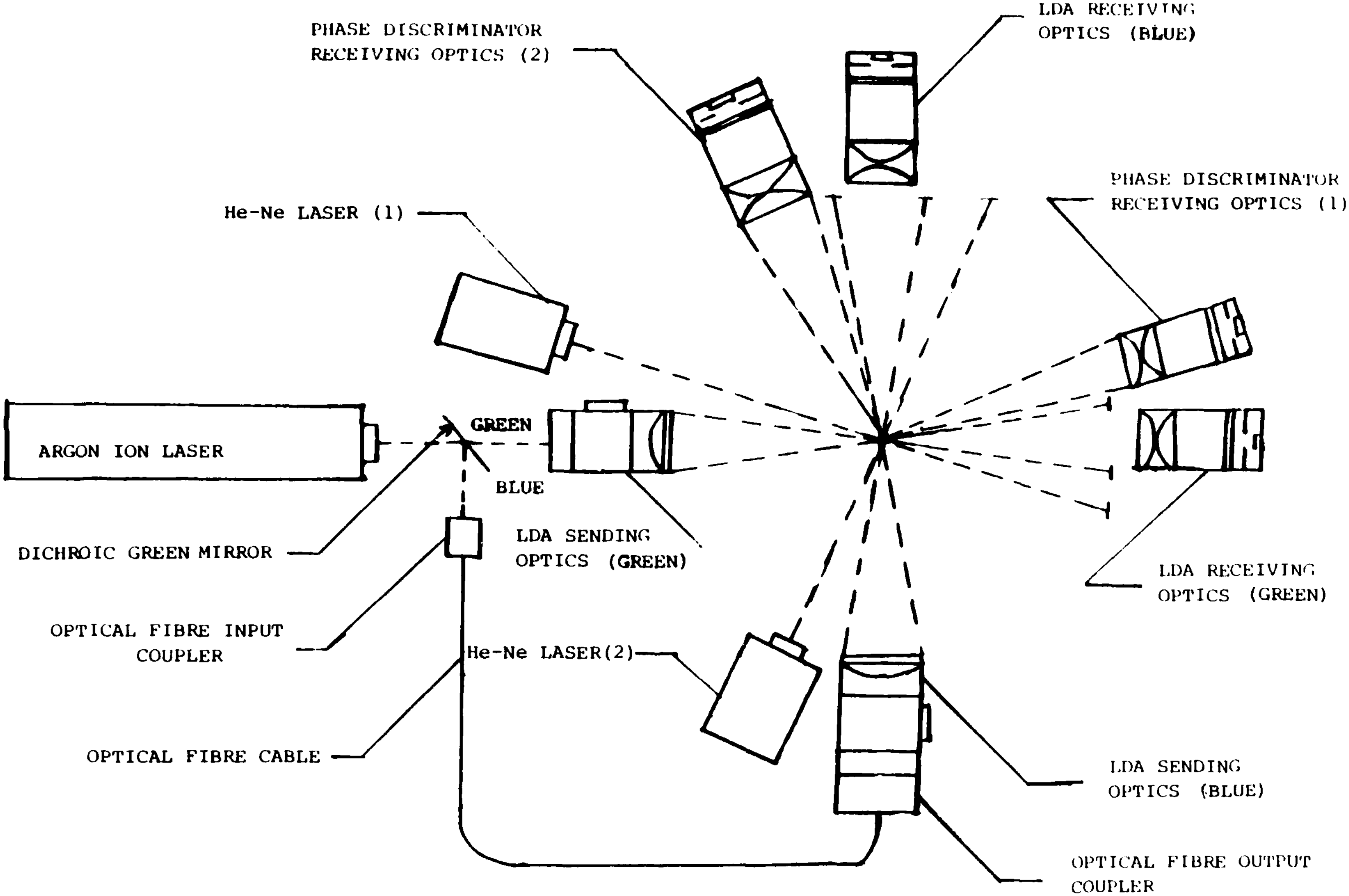

Figure 9. Sketch of two-channel/two-point/phase-discriminating laser-Doppler anemometer.

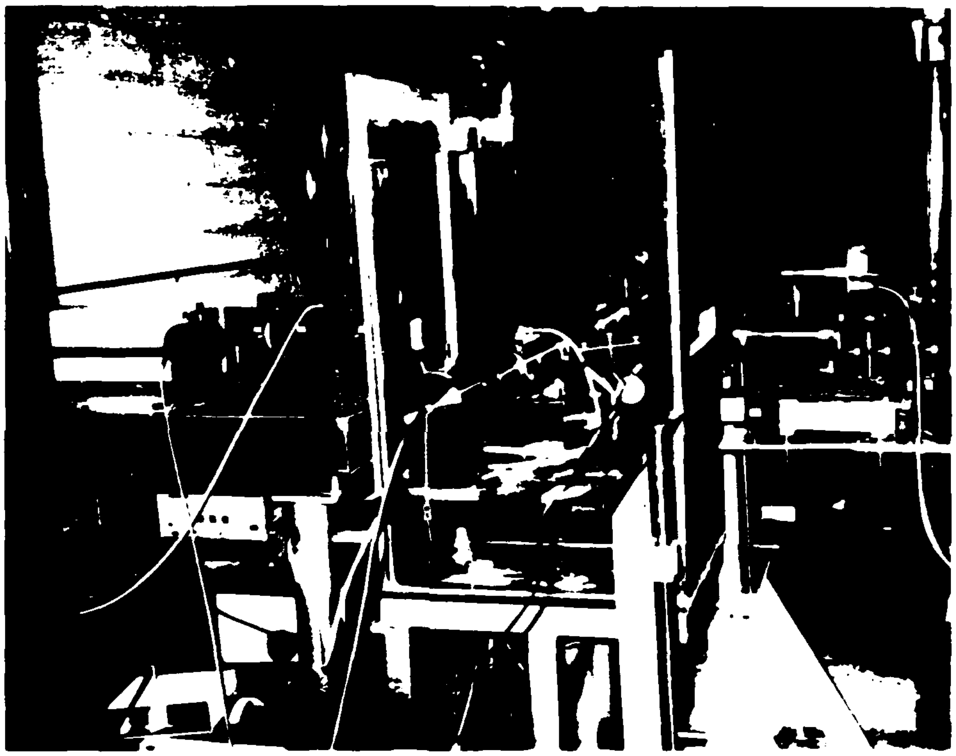

Figure 10. Photograph of two-channel/two-point/phase-discriminating laser Doppler anemometer.

phase-discriminator detectors are at the far side of the tank and receive signals through appropriate line filters.

The blue laser beam is directed to an optical fiber which supplies the traversable LDA. The arrangement is similar to the fixed LDA, except that the laser power of the HeNe beam differs from the stationary channel, to allow differentiation between the discriminator signals when the two measuring volumes are close to each other.

Since the flow being studied is homogeneous, there is no need to have both LDA oriented at similar angles in the horizontal plane. The right angle configuration, shown in Figs. 9 and 10, was selected for convenience when using a rectangular tank. The movable LDA can traverse horizontally along the optical axis of the stationary LDA, to find crosstream properties; and in the vertical direction, to find streamwise properties.

Output signals from the LDA are processed using two burst counters. The final four LDA and phase-discrimination signals are collected using a LeCroy sampling system and processed using the IBM 9002 microcomputer.

Three test conditions have been established, identified according to particle number fluxes as low, medium and high. The properties of these three conditions are summarized in Table 3. Glass beads having a diameter of 1 mm are used, with particle loadings yielding mean particle spacings in the range 18-33 mm. The terminal velocity of the particles in still water is 149 mm/s. The particles generate velocity fluctuations in the liquid which are roughly an order of magnitude smaller than the terminal velocity.

The test arrangement and phase-discriminating LDA have been operated and performed satisfactorily. Measurements of power spectra indicate that the particles generate a very respectable turbulence field, with a reasonably-large inertial range, in spite of the low velocity fluctuation levels. Complete measurements for the test conditions of Table 3 are just getting underway; however, it is already clear that the instrument will provide unique and interesting measurements for this important class of multiphase flows. The arrangement has excellent potential for finally quantifying turbulence modulation and other turbulence/dispersed-phase interactions.

3.3 Future applications.

Fully exploiting the two-channel/two point phase-discriminating LDA will be a major use of the instruments acquired under this grant. However, other findings in connection with the study of dense sprays provide potential applications for the system, when in the phase-Doppler configuration.

Table 3. Summary of Turbulence Modulation Test Conditions⁺

Flow	Low	Medium	High
Particle flux (part./m^2s)	3670	9160	20930
Particle spacing (mm)	32.7	24.1	18.3
Streamwise velocity fluctuations (mm/s)	5.1	8.0	10.6

⁺Glass beads, 1 mm diameter with a density of 2450 kg/m^3, falling in a stagnant water bath at 298 ± 2K. Terminal velocity of particles in still water is 149 mm/s.

The nature of the dense-spray investigation, and the findings thus far, are summarized by Ruff et al. (1987, 1987a). An important issue for dense sprays involves the applicability of the locally homogeneous flow (LHF) approximation of multiphase flow theory (the LHF approximation implies that relative phase velocities (slip) are small in comparison to the mean velocity of the flow). Findings thus far suggest that the LHF approximation is adequate for determining the mean liquid volume fraction distributions and mixing properties of dense sprays when the flow is in the atomization breakup regime. However, this information provides a relatively insensitive evaluation to the LHF approach and leaves open questions concerning why the approach is effective in some instances and not in others.

A more definitive way to evaluate the LHF approximation is to directly measure phase velocities in the flow. Interpreting these results requires information on drop size distributions as well. Both measurements are a logical application of the phase-Doppler approach; therefore, this configuration will be used for the experiments. Fortunately, recent measurements have shown that the drop-containing region of dense sprays is not as heavily-loaded with drops as thought earlier; thus, use of phase Doppler for the work appears to be feasible.

4. Summary of Investigation

4.1 Articles and Papers

Faeth, G. M. (1987) Structure of nonpremixed and premixed combusting pressure-atomized sprays. Proceedings of the Twentieth Fall Technical Meeting, Eastern Section of the Combustion Institute, Pittsburgh, invited.

Faeth, G. M. (1987) Turbulent multiphase flows. Proceedings of the U.S.-France Workshop on Turbulent Reactive Flows, Springer-Verlag, Berlin, in press.

Parthasarathy, R.N. & Faeth, G. M. (1987) Structure of particle-laden turbulent water jets in still water. Int. j. Multiphase Flow, in press.

Parthasarathy, R. N. & Faeth, G. M. (1987) Structure of turbulent particle-laden jets having comparable phase densities. Proceedings of the 1987 Spring Technical Meeting, pp. 64.1-64.4, Central States Section of the Combustion Institute, Pittsburgh.

4.2 Participants.

G. M. Faeth, Principal Investigator; Professor, The University of Michigan.

R. N. Parthasarathy, Graduate Assistant, Doctoral Candidate, The University of MIchigan.

4.3 Oral presentations.

G. M. Faeth, "Turbulence/Drop Interactions in Sprays," Southwest Mechanics Seminar Series: Southwest Research Institute, San Antonio; University of Houston, Houston; and Shell Development Company, Houston, October 1986.

G. M. Faeth, "Turbulence/Particle Interactions in Dilute Particle-Laden Liquid Jets," Department of Mechanical Engineering, Carnegie-Mellon University, Pittsburgh, February 1987.

G. M. Faeth, "Particle-Laden Jets having Comparable Phase Densities," Chemical and Physical Sciences Laboratory Seminar Series, Ford Scientific Research Laboratories, Dearborn, MI, March 1987.

G. M. Faeth, "Turbulent Multiphase Flows," U.S.-France Workshop on Turbulent Reactive Flows, University of Rouen, France, July 1987.

G. M. Faeth, "Structure of Nonpremixed and Premixed Combusting Pressure-Atomized Sprays," Fall Technical Meeting, Eastern Section of the Combustion Institute, Gaithersburg, MD, November 1987.

R. N. Parthasarathy, "Structure of Turbulent Particle-Laden Jets having Comparable Phase Densities," Spring Technical Meeting, Central States Section of the Combustion Institute, Argonne, IL, May 1987.

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Ruff, G. A., Sagar, A. D. & Faeth, G. M. (1987) Structure of large-scale pressure-atomized sprays. First Annual Conference of ILASS-Americas, Madison, WI.

Ruff, G. A., Sagar, A. D. & Faeth, G. M. (1987a) Structure and mixing properties of pressure-atomized sprays. AIAA 26th Aerospace Sciences Meeting, Reno, NV, submitted.

Shuen, J.-S., Solomon, A.S.P. & Faeth, G. M. (1986) Drop-turbulence interactions in a diffusion flame. AIAA J. 24, 101-108.

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Solomon, A.S.P., Shuen, J.-S., Zhang, Q.-F. & Faeth, G. M. (1985a) Measurements and predictions of the structure of evaporating sprays. J. Heat Transfer 107, 679-686.

Sun, T.-Y. & Faeth, G. M. (1986) Structure of turbulent bubbly jets. – I. Methods and centerline properties; – II. Phase property profiles. Int. J. Multiphase Flow 12, 99-126.

Sun, T.-Y., Parthasarathy, R. N. & Faeth, G. M. (1986) Structure of bubbly round condensing jets. J. Heat Transfer 108, 951-959.

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